TN NO. 64T 6

UNITED STATES NAVAL POSTGRADUATE SCHOOL

DEPARTMENT OF AERONAUTICS

TECHNICAL NOTE

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DETERMINATION OF THE MOMENTUM DRAG

WITHIN THE

TURBOJET ENGINE LABORATORY

WHILE OPERATING THE J-57-8B TURBOJET ENGINE

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ABSTRACT

Limited tests were conducted at the USNPGS Astro/Aeronautical Propulsion Laboratories to determine the magnitude and variation of the momentum drag which is developed within turboject engine test chamber while operating a J-57-8B powerplant. A survey of the aerodynamic characteristics at the chamber inlet and the calculation of the momentum and energy interchange at the engine exhaust plane reveal that this restrictive drag which penalizes the "indicated" performance of the engine is approximately 1.0% of the thrust output and varies directly with the ratio of engine thrust to secondary airflow.

Further tests will be necessary to evaluate the effects of the positioning of the exhaust augmenter and the variation of the exhaust cooling water flow rate upon the secondary airflow and the resulting momentum drag. With the completion of these surveys it is anticipated that the over-all accuracy of the facility thrust measuring system will be ± 0.50% throughout the thrust range of 1000 to 30,000 lbs.

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INTRODUCTION

Turbojet engines operated in enclosed test facilities experience simulated forward velocities as high as 40 miles per hour. This velocity relative to the airflow moving rearward through the test chamber introduces a drag force which is opposite to the engine thrust and is similar to the "ram drag" that prevails upon an aircraft in motion. As a result of this drag component the engine indicated thrust is less than the actual value. Therefore in order to determine the exact performance of any engine, the "momentum drag" must be properly identified and incorporated in the test data.

Momentum drag results primarily from the large mass of secondary airflow moving through the test chamber which is induced by the development of a region of low pressure at the engine exhaust plane. The secondary airflow is admitted into the chamber through the same inlet passage which supplies the engine airflow requirements. This secondary airflow is normally one to five times larger than the engine airflow values and results in the creation of momentum drag levels which are 1.0 to 3.0% of the engine indicated thrust.

The determination of momentum drag can be accomplished by measurement of the secondary airflow and engine airflow and calculation of the momentum losses through the test chamber, or by correlation of engine data from a "calibrated" test engine which had been operated in a test chamber with established correction factors. Exact correlation is also possible by correlating data from an engine operated on an outdoor test stand where the drag force would be zero; however such precision test sites are uncommon due to the uncontrolled environment and the excessive noise levels.

The measurement of the primary and secondary airflows and the calculation of the momentum drag is the procedure incorporated at most research test chambers and will be the method utilized at the USNPGS for accomplishing the test objectives listed below.

TEST OBJECTIVES

The test program being initiated at the USNPGS Turbojet Test Laboratory shall accomplish the following objectives:

a. Obtain a facility thrust measuring system with overall accuracies of $\pm$ 0.50% of the indicated thrust levels.

b. Determine the effects of augmenter tube spacing, exhaust water flow rates and inlet blockage upon the momentum drag variation with power setting.

c. Determine the effects of various engine configurations upon the momentum drag, i.e., variable exhaust nozzles, ejectors, afterburners, turbofan ducting and airframe equipment.

The following resume covers the activities to resolve step (a) and is limited to the validation of the subject chamber instrumentation system when operating a J-57 turbojet engine with afterburner. The test program was further restricted by maintaining a constant spacing between the engine exhaust plane and the augmenter. Also the amount of cooling water injected into the exhaust passage was held at a constant value.

TEST EQUIPMENT

The powerplant utilized for this basic validation of the subject system was a J-57-8B engine with afterburner. The engine, which was recently overhauled at the Overhaul and Repair Department, NAS North Is-

land, has been instrumented for thermodynamic analysis of the propulsion cycle and is utilized for academic purposes. The USNPGS Turboject Engine Test Chamber shown in Figure 1 is similar in design to the Navy Class "C" Test Cells. The engine support stand and thrust measuring assembly is identical to the configuration at the Naval Air Turbine Test Station. This assembly with the long flexure columns shown in Figure 2 permits free movement of the engine and the support stand along the thrust centerline due to the neglible restrictive spring force in the flexure plates.

The engine instrumentation and control systems are primarily the same as those found in the Class "C" chambers. Additional instrumentation was required for the measurement of the engine airflow and the facility inlet airflow. Engine airflow was derived by using total and static pressure probes installed in the compressor inlet and a multiple tube manometer bank located in the control room. The total airflow was determined through the use of a manifolded rake containing total and static probes. The dynamic pressures were observed on a single tube manometer located in the inlet passage area shown in Figure 3.

TEST SEQUENCE

The J-57 engine was operated at various power settings from approximately 5,000 lbs., indicated thrust to Maximum Afterburner, 15,000 lbs. At each setting the engine was stabilized before data were recorded. The primary engine parameters were noted simultaneously with the recording of the dynamic pressures for airflow calculation. The single rake was moved to twenty eight (28) stations in the inlet passage and the

average dynamic pressure was noted at each location. The total operating time for each data point, including stabilizing of the engine, was approximately ten minutes.

The J-57 engine was "trimmed" to conform to the minimum performance limits specified for Military and Maximum Afterburner power in NAVWEPS 02B-10ADC-503A. With the engine fuel control adjusted to reflect these precise limits, the engine guaranteed thrust for these two power settings was then available for correlation with the actual observed values.

During afterburner operation it was necessary to inject cooling water into the exhaust augmenter to maintain the facility exhaust passage temperatures below 350°F. The water flow rate was held at a constant value regardless of afterburner power setting. Water was not required in the non-afterburning range.

The engine data were compiled and corrected to standard sea level conditions shown in Table 1. The engine airflow was calculated from the average dynamic pressures at the compressor inlet, while the total airflow into the test chamber was determined from the average pressures shown in Table 2. The secondary airflow was then found from the difference between the total and engine airflow. The airflow values, corrected to standard sea level conditions, are shown in Table 3.

The momentum drag was determined from the energy equations which relate the momentum and energy changes occuring between stations immediately preceding and immediately following the engine. The derivation of these relationships and the simplifying assumptions are shown in Table 4; while the resulting momentum drag values from the subject test sequence are noted in Table 5.

RESULTS

The momentum drag acting upon the J-57 engine in the subject test chamber varied as shown in Figure 4 from approximately 80 lbs., at the minimum cruise power region to 130 lbs., at maximum afterburner operation. The momentum drag variation was noted to be linear with the ratio of thrust to secondary airflow for all power settings above 6000 lbs., indicated thrust. It is believed that the data below this region is affected by the actuation of the compressor bleed valves which reduce the engine mass flow.

Noting that the engine was "trimmed" at the minimum operating limit, the actual thrust, when corrected to standard sea level conditions, should conform to the values specified in NAVWEPS 02B-10ADC-503A. The corrected test data indicate that the military power indicated thrust adjusted for the momentum drag restriction is 18 lbs. below the required limits whereas the maximum afterburning thrust with the momentum drag included is 7 lbs. below the operating line. The neglible deviation between the USNPGS test data and the NAVWEPS specifications indicates that the relative value of the momentum drag is of the proper order of magnitude. The guaranteed operating line and the two "trim" points are shown in Figure 5.

The results shown in Figure 5 indicate that the accuracy of the USNPGS thrust measuring system is well within the desired range of $\pm 0.5\%$ of the indicated thrust.

CONCLUSION

The test sequence and the instrumentation described above are sufficient to determine all of the necessary parameters for calculation of

momentum drag in the USNPGS turbojet engine test facility. The momentum drag equation yields values which agree closely with the expected and desired results.

The USNPGS thrust measuring system in the turbojet engine test chamber is well within $\pm$ 0.5% of the indicated thrust values for the operating range of 6000 to 16,000#.

USNPGS Turbojet Engine Test Chamber

ENGINE PERFORMANCE DATA

Table 1

Test Time: 1430 Test Date: 5 August 64 J-57-8B (S/N 604339)

Quantity	Units	Milit.		Power Settings Cruise		Idle	Max. A/B	Min. A/B
F_{gg_i}	Lbs.	9950	9000	7000	5860	500	15650	12960
F_{g_i}/δ_2	Lbs.	9990	9020	7010	5875	502	15710	13000
F_g/δ_2(Guar.)	Lbs.	10120	--	--	--	--	15850	--
W_f	PPH	8750	7750	5900	5000	1325	34700	30000
$W_f/\sqrt{\theta_2}\delta_2$	PPH	8770	7770	5910	5010	1330	34810	30070
EGT/θ_2	^{o}F	1070	990	865	790	570	1075	970
$N_1/\sqrt{\theta_2}$	RPM	5830	5661	5261	5028	1853	5773	5360
$N_2/\sqrt{\theta_2}$	RPM	9396	9256	8908	8706	5578	9381	9125
P_{T_7}	In HgA	68.95	66.45	57.55	51.45	32.65	69.45	63.65
Eng. Press. Ratio		2.32	2.22	1.92	1.72	1.09	2.32	2.13
Compressor Inlet Dynamic Pressures								
$P_t - P_s$ (1)	In H_2O	34.1	31.3	24.9	21.2	2.0	33.8	27.0
$P_t - P_s$ (2)	In H_2O	34.7	31.9	25.0	21.6	2.0	34.3	27.6
$P_t - P_s$ (3)	In H_2O	39.8	36.7	29.8	24.9	2.0	39.7	31.7
$P_t - P_s$ (4)	In H 0	35.0	32.1	25.4	21.8	2.0	34.8	27.7
$P_t - P_s$ AVE.	In H 0	35.9	33.0	26.3	22.3	2.0	35.6	28.5

Barometric Pressure - 29.815 In HgA, Ambient Temperature - $60^{o}F$

NOTE: F_{g_i}/δ_2 is not corrected for the momentum drag losses.

USNPGS Turbojet Engine Test Chamber

INLET PASSAGE DYNAMIC PRESSURE SURVEY

Time: 1430 Table 2 5 August 64

Power Setting: Military Ave. Dynamic Pressure = 0.602 In H_2O

Passages Between Acoustic Baffles

Axial Position Along The Chamber Centerline		1	2	3	4	5	6	7
	A	.4	.5	.6	.6	.6	.6	.6
	B	.4	.7	.6	.7	.6	.7	.8
	C	.6	.6	.7	.7	.7	.7	.8
	D	.4	.6	.5	.6	.5	.5	.5

Dynamic Pressures - In H_2O

Power Settings: F_{g_i} = 9000 Lbs.; Ave. Dynamic Pressure = 0.575 In H_2O

Axial Position Along The Chamber Centerline								
	A	.4	.5	.7	.6	.6	.6	.6
	B	.4	.6	.7	.7	.6	.7	.7
	C	.3	.7	.7	.6	.7	.7	.7
	D	.4	.6	.6	.5	.6	.5	.5

Dynamic Pressures - In H_2O

Power Setting: F_{g_i} = 7000 Lbs.; Ave. Dynamic Pressure = 0.541 In H_2O

Axial Position Along The Chamber Centerline								
	A	.4	.4	.5	.5	.6	.6	.6
	B	.4	.5	.6	.6	.7	.6	.6
	C	.6	.6	.7	.6	.6	.6	.6
	D.	.4	.5	.4	.5	.5	.5	.5

Dynamic Pressures - In H_2O

Power Setting: F_{g_i} = 5860 Lbs.; Ave. Dynamic Pressure = 0.468 In H_2O

Axial Position Along The Chamber Centerline								
	A	.5	.5	.5	.5	.5	.4	.5
	B	.5	.5	.5	.5	.5	.5	.5
	C	.3	.6	.6	.6	.5	.5	.5
	D	.3	.5	.3	.4	.5	.4	.3

Dynamic Pressures - In H_2O

Power Setting: F_{g_i} = 13000 Lbs.; Ave Dynamic Pressure = 0.761 In H_2O

Axial Position Along The Chamber Centerline								
	A	.8	.9	.8	.7	.8	.8	.8
	B	.7	.9	.8	.9	.9	.8	.7
	C	.6	.8	.8	.8	.7	.7	.9
	D	.5	.7	.8	.8	.7	.6	.6

Dynamic Pressures - In H_2O

Power Setting: Maximum Afterburner; Ave Dynamic Press. = 0.807 In H_2O

Axial Position Along The Chamber Centerline								
	A	.5	.8	.8	.8	.8	.9	.9
	B	.7	.8	.9	.9	1.0	1.0	1.0
	C	.4	.8	.9	.8	.9	.9	.9
	D	.4	.8	.9	.8	.8	.8	.7

Dynamic Pressures - In H_2O

USNPGS Turbojet Engine Test Chamber

AIRFLOW CALCULATION SUMMARY

Table 3

Indicated Thrust (Corrected)	Lbs.	5875	7010	9020	9990	13000	15710
Facility Inlet Dynamic Pressure	In.H_2O	.468	.541	.575	.602	.761	.807
Facility Inlet Velocity	Ft/Sec	45.2	48.6	50.2	51.2	57.6	59.4
Total Airflow Into Chamber	Lb/Sec	502	540	556	568	640	660
Engine Inlet Dynamic Pressure	In.H_2O	22.3	26.3	33.0	35.9	28.5	35.6
Engine Inlet Velocity	Ft/Sec	312	339	380	396	353	394
Engine Inlet Airflow	Lbs/Sec	131	143	160	166	149	166
Secondary Airflow	Lbs/Sec	371	397	396	402	491	494
Ratio of Thrust to Secondary Air	Lbs/PPS	15.8	17.6	22.8	24.9	26.5	31.8
Engine Airflow (Corrected)	Lbs/Sec	131	143	161	167	149	167
Secondary Airflow (Corrected)	Lbs/Sec	372	398	397	403	493	496

Remarks:

Compressor Inlet Area	5.50 Sq.Ft.
Chamber Inlet Area	150 Sq.Ft.
Engine Exhaust Area	7.85 Sq.Ft.
Secondary Airflow Area	287 Sq.Ft.
Chamber Cross-sectional Area	295 Sq.Ft.
Ambient Pressure	60^{o}F
Ambient Temperature	29.815 InHgA

USNPGS Turbojet Engine Test Chamber

DERIVATION OF THE MOMENTUM DRAG EQUATION

Table 4

The energy balance between two stations within the test chamber is expanded below. The two stations are located immediately forward and aft of the engine:

$$\frac{1}{g}(W_1V_1) + P_1A_1 + F_{g_i} = \frac{1}{g}(W_{8_s}V_{8_s}) + P_{8_s}A_{8_s} + \frac{1}{g}(W_{8_e}V_{8_e}) + P_{8_e}A_{8_e}$$

Since the thrust of the engine is given by:

$$F_g = \frac{1}{g}(W_{8_e}V_{8_e}) + P_{8_e}A_{8_e} - P_{8_s}A_{8_e}$$

Then:

$$F_g - F_{g_i} = \Delta F_{MD} = \frac{1}{g}(W_1V_1) + P_1A_1 - \frac{1}{g}(W_{8_s}V_{8_s}) - P_{8_s}A_{8_s} - P_{8_s}A_{8_e}$$

Using the Mass Flow Equation: $P_t - P_s = 2\,\frac{1}{g}\left(\frac{WV}{A}\right)$

$$F_g - F_{g_i} \equiv \frac{1}{2g}(W_1V_1) - \frac{1}{2g}(W_{8_s}V_{8_s})(1 - A_{8_e}/A_{8_s})$$

Using $V = W/\rho A$ and assuming $\rho_1 = \rho_8$:

$$F_g - F_{g_i} = \frac{1}{2g\rho_1}\left[\left[(W_1)^2/A_1 - [(W_{8_s})^2/A_{8_s}][1 - A_{8_e}/A_{8_s}]\right]\right]$$

Since: $W_8 = W_1 - W_{eng.}$

$$F_g - F_{g_i} = \frac{1}{2g\rho_1}\left[\left[(W_1)^2/A_1 - \left[(W_1 - W_{e_1})^2/A_8\right]\right]\left[(1 - A_{8_e}/A_{8_s})\right]\right]$$

Using Corrected Airflow Values and Standard Seal Level Density:

$$F_g - F_{g_i} = .2029\left[\frac{(W_1)^2}{295} - \frac{(W_1 - W_{e1})^2}{287}(.9727)\right]$$

Reference:
General Electric Co., Technical Information Series, AGT-204 "Handbook for Test Cell Corrections".

USNPGS Turbojet Engine Test Chamber

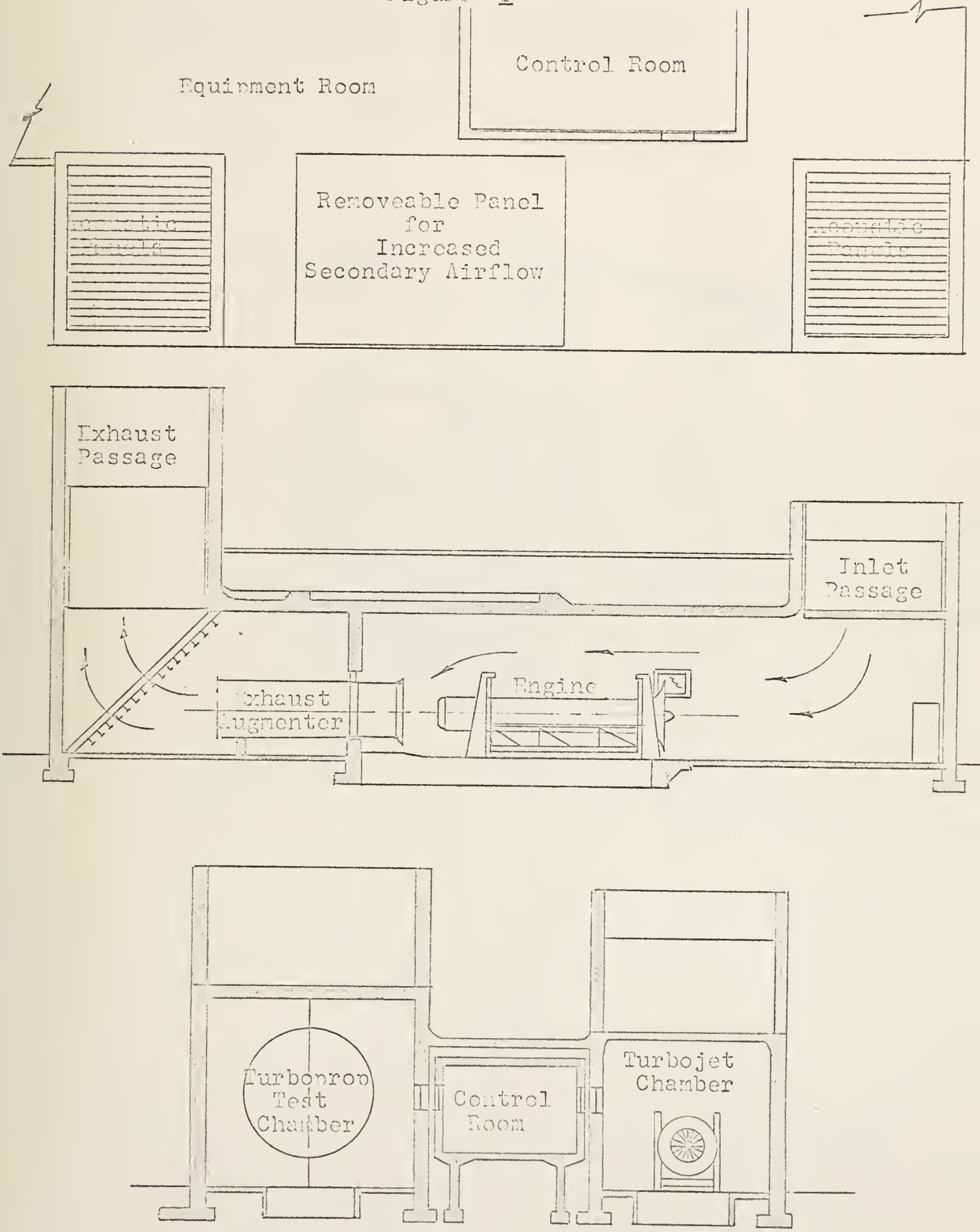
MOMENTUM DRAG CALCULATIONS

Table 5

Indicated Thrust F_{g_i}/δ_2 (LBS)	5875	7010	9020	9990	1300	15710
Facility Inlet Airflow $W_1\sqrt{\theta_2}/\delta_2$ (PPS)	503	541	558	570	642	663
Engine Airflow $W_{e_1}\sqrt{\theta_2}/\delta_2$ (PPS)	131	143	161	167	149	167
Secondary Airflow $W_{8_s}\sqrt{\theta_2}/\delta_2$ (PPS)	372	398	397	403	493	496
MOMENTUM DRAG $F_g - F_{g_i}/\delta_2$ (LBS)	79	92	106	112	116	133
Actual Thrust F_g/δ_2 (LBS)	5954	7102	9125	10102	13116	15843
Guaranteed Thrust F_g/δ_2 (LBS)	(NAVWEPS Specification)			10120		15850

USNPGS TURBOJET ENGINE TEST CHAMBER

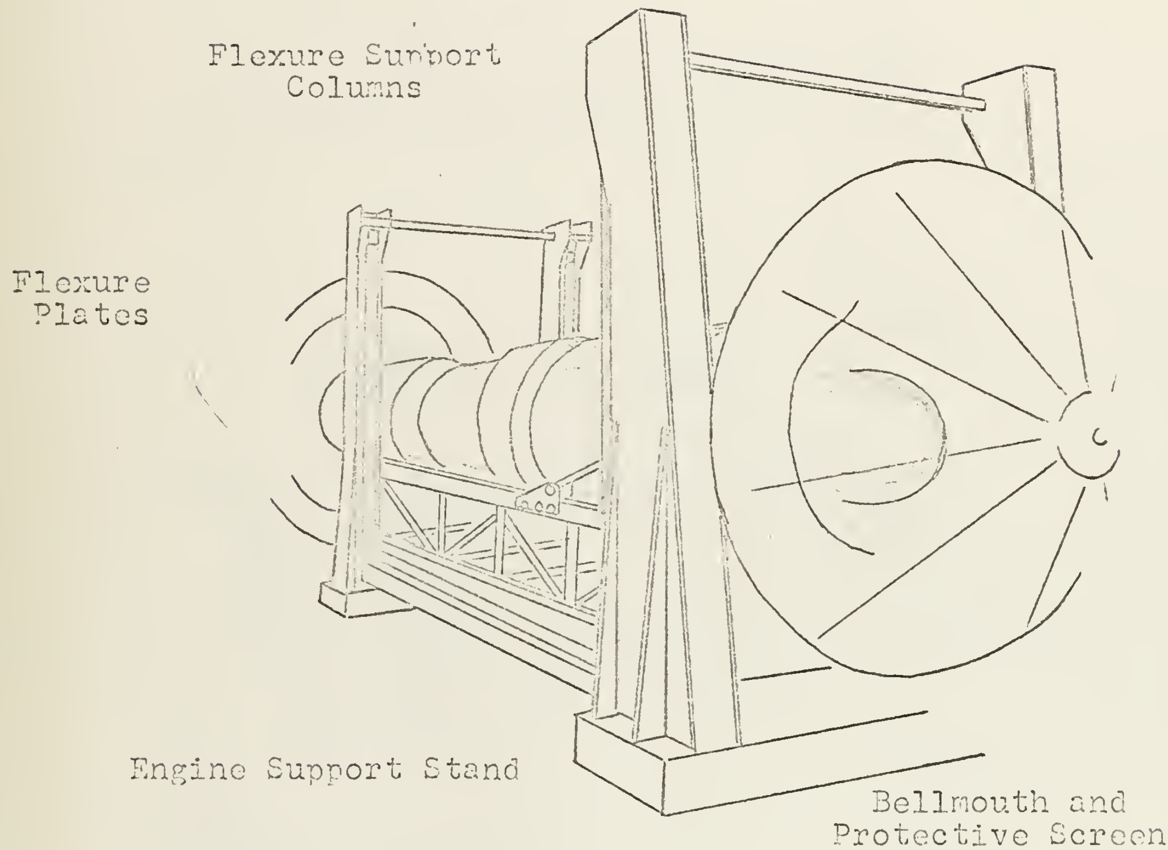
Figure 1



USNPGS Turbojet Engine Test Chamber

ENGINE SUPPORT STAND AND FLEXURE ASSEMBLY

Figure 2



NOTE: Engine support stand configuration is compatible with Class "C" Chamber special support and handling equipment.

USNPGS Turbojet Engine Test Chamber

TEST CHAMBER INLET PASSAGE WITH AIRFLOW INSTRUMENTATION

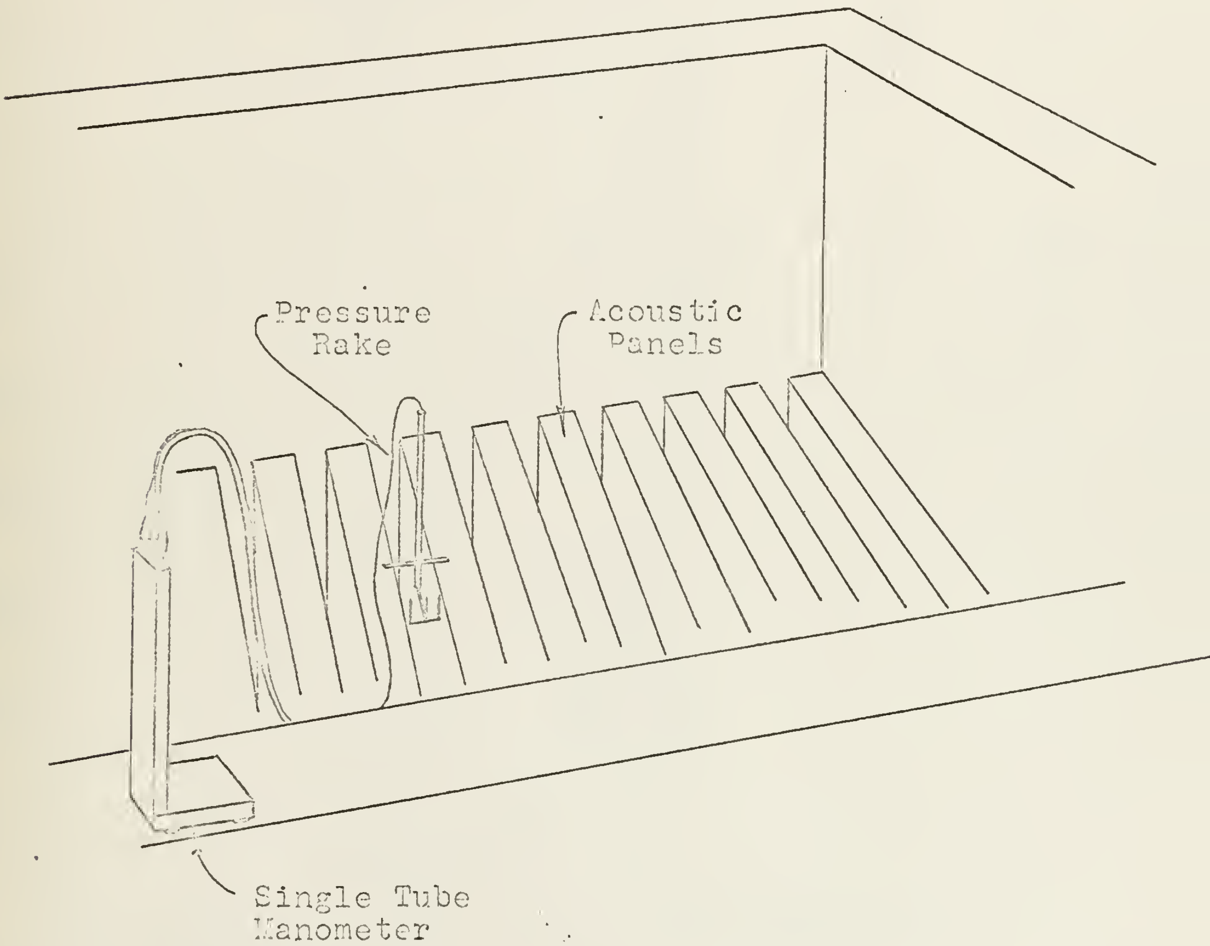
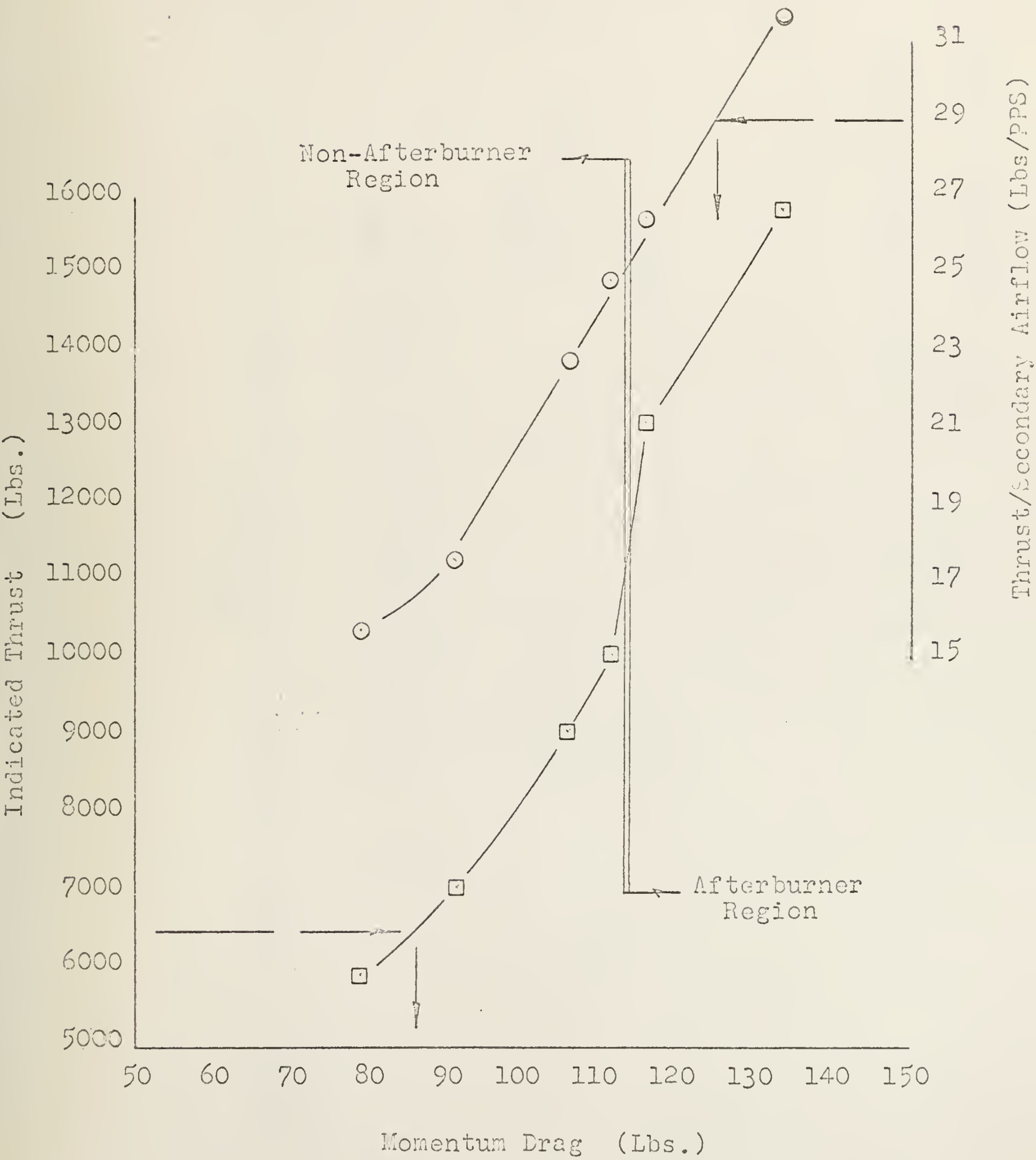


Figure 3

USNPGS Turbojet Engine Test Chamber

MOMENTUM DRAG VARIATION WITH THRUST AND SECONDARY AIRFLOW

Figure 4



USNPGS Turbojet Engine Test Chamber

<u>Guaranteed Thrust Variation With Engine Pressure Ratio</u>

Figure 5

NOTE: Minimum operating line derived from NAVWEPS 02B-10ADC-503A